

Establishing maximal oxygen uptake in young people during a ramp cycle test to exhaustion

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ABSTRACT

Objectives This study tested the hypotheses that (1) secondary criteria (respiratory exchange ratio (RER), heart rate, blood [lactate]) traditionally used to verify the determination of maximum oxygen uptake ($\dot{V}O_{2max}$) in children can result in the acceptance of a 'submaximal' $\dot{V}O_{2max}$ or falsely reject a 'true' $\dot{V}O_{2max}$ and (2) the $\dot{V}O_{2peak}$ recorded during a ramp test in children is comparable to the $\dot{V}O_{2peak}$ achieved during supramaximal testing.

Methods Thirteen children (9–10 years) completed a ramp cycle test to exhaustion to determine their $\dot{V}O_{2peak}$. After 15 min of recovery, the participants performed a supramaximal cycle test to exhaustion at 105% of their ramp test peak power.

Results Compared with the $\dot{V}O_{2peak}$ during the ramp test, a significantly lower $\dot{V}O_2$ was recorded at a RER of 1.00 (1.293 litre/min (SD 0.265) vs 1.681 litre/min (SD 0.295), $p < 0.001$, $n = 12$), at a heart rate of 195 beats/min (1.556 litre/min (SD 0.265) vs 1.721 litre/min (SD 0.318), $p < 0.001$, $n = 10$) and at 85% of age-predicted maximum (1.345 litre/min (SD 0.228) vs 1.690 litre/min (SD 0.284), $p < 0.001$, $n = 13$). Supramaximal testing yielded a $\dot{V}O_{2peak}$ that was not significantly different from the ramp test (1.615 litre/min (SD 0.307) vs 1.690 litre/min (SD 0.284), $p = 0.090$, respectively).

Conclusions The use of secondary criteria to verify a maximal effort in young people during ramp cycling exercise may result in the acceptance of a submaximal $\dot{V}O_{2max}$. As supramaximal testing elicits a $\dot{V}O_{2peak}$ similar to the ramp protocol, thus satisfying the plateau criterion, the use of such tests is recommended as the appropriate method of confirming a 'true' $\dot{V}O_{2max}$ with children.

Keywords Children, Aerobic Fitness, Fitness Testing, Supramaximal Exercise.

Maximum oxygen uptake ($\dot{V}O_{2max}$) is widely recognised as the best single measure of aerobic fitness.¹ In young people, $\dot{V}O_{2max}$ is a key outcome measure in studies investigating the development of aerobic fitness,² trainability of the cardiorespiratory system,³ relationships between physical activity, fitness and health,⁴ and cardiorespiratory (dys)function in disease.⁵ However, the most appropriate methods to measure and interpret $\dot{V}O_{2max}$ in this population remain controversial.^{6–8}

The traditional paradigm for $\dot{V}O_{2max}$ determination requires that during exercise close to exhaustion, in a well-motivated participant $\dot{V}O_2$ will no longer increase linearly with the exercise intensity but rather display a plateau.^{9 10} However, because only ~20–40% of children performing

exercise to exhaustion display a plateau in their $\dot{V}O_2$ response,^{6 11 12} it has become conventional to use the term 'peak $\dot{V}O_2$ ' ($\dot{V}O_{2peak}$). That is, the highest $\dot{V}O_2$ recorded during an exercise test to volitional exhaustion. Because children who exhibit a plateau are indistinguishable from those who do not,^{6 11} these findings raise a fundamental question: has $\dot{V}O_{2max}$ been 'truly' attained? Rowland¹³ and Armstrong *et al*¹⁴ used supramaximal running to exhaustion at treadmill gradients 2.5–7.5% greater than that achieved during an initial incremental test and found no differences in the $\dot{V}O_{2peak}$ attained across the two protocols in children aged 10–12 years. These data therefore imply that a 'true' $\dot{V}O_{2max}$ had in fact been achieved during the initial incremental protocol despite the absence of a plateau in most of the participants during the incremental test.

In contrast to incremental treadmill protocols used by Rowland¹³ and Armstrong *et al*,¹⁴ a cycling protocol where power output is increased linearly with time ('ramp' exercise) is becoming a popular method for determining $\dot{V}O_{2max}$ both in healthy and diseased children.^{5 15 16} This is because of its short test duration (8–12 min) and because other key parameters of aerobic function (gas exchange threshold, exercise economy, kinetic response time) can be determined during the test.¹⁷ However, despite it having been demonstrated that the $\dot{V}O_{2peak}$ determined using a ramp test is as reliable in children as it is in adults, with a typical error across three tests of ~4.0%,¹⁸ it remains to be established whether the highest $\dot{V}O_2$ attained using ramp cycling exercise reflects a 'true' $\dot{V}O_{2max}$.

As children rarely exhibit a $\dot{V}O_2$ plateau, paediatric researchers rely on subjective indicators of intense effort (eg, facial flushing, sweating, unsteady gait, hyperpnoea) and secondary 'objective' criteria (eg, respiratory exchange ratio (RER), blood [lactate] and heart rate thresholds) to verify a 'maximal' response.^{6 19 20} However, recent studies of healthy adults have questioned the validity of using secondary criteria during ramp exercise, as RER, heart rate and blood lactate criteria can underestimate $\dot{V}O_{2max}$ by 30–40% or falsely reject a valid $\dot{V}O_{2max}$ measure.^{21 22} As previous maximal exercise studies of children have documented a large interindividual variation in RER (range 0.95–1.15), heart rate (range 185–215 beats/min) and blood [lactate] (range 3–12 mM) at exhaustion,^{6 13 19} it is plausible that the use of such secondary criteria is equally inappropriate in young people.

The aims of this study are to test the following hypotheses: (1) that commonly used secondary

criteria to verify a $\dot{V}O_{2\max}$ in children can result in the acceptance of a submaximal $\dot{V}O_{2\max}$ during ramp cycling exercise or falsely reject a 'true' $\dot{V}O_{2\max}$; and (2) that the $\dot{V}O_{2\text{peak}}$ recorded during a ramp incremental test in children is comparable to the $\dot{V}O_{2\text{peak}}$ achieved during supramaximal testing, thus satisfying the plateau requirement for a true $\dot{V}O_{2\max}$.

METHODOLOGY

Participants

Thirteen 9- to 10-year-old children (eight boys and five girls) volunteered to take part in the study. The participants' mean body mass and stature were 33.8 kg (SD 5.71) and 1.375 m (SD 0.077), respectively. All children and their parent(s) or guardian(s) provided informed assent and consent to partake in the project, which was approved by the institutional ethics committee. The children were healthy, recreationally active and showed no contraindications to exercise to exhaustion.

Ramp and supramaximal exercise

All tests took place on an electronically braked cycle ergometer (Lode, Groningen, The Netherlands), with appropriate adjustments made to the ergometer seat, handlebar and pedal cranks for each participant. After a 3-min period of cycling at 10 W, a ramp incremental test to exhaustion was undertaken with power output increasing by 10 W/min. Participants cycled at ~75 rpm throughout the test. Exhaustion was defined as a drop in cadence below 60 rpm for five consecutive seconds. Immediately after exhaustion, power output was lowered to 10 W and the participant cycled at this intensity for 10 min followed by 5 min of rest. Subsequently, the participant performed a supramaximal exercise bout consisting of 2 min of pedalling at 10 W and a 'step' transition to 105% of the peak power achieved during the ramp test. Participants cycled at this intensity with a pedal rate of ~75 rpm until exhaustion, as defined above. Power output was then returned to 10 W until heart rate recovered to ~120 beats/min.

Experimental measures

Breath-by-breath changes in gas exchange and ventilation were measured and displayed using an online system (EX671; Morgan Medical, Kent, UK). Gas fractions of O_2 and CO_2 were drawn continuously from a low dead space (90 ml) mouth-piece-turbine assembly and determined by mass spectrometry. Expired volume was measured by a turbine flow meter (VMM-401; Interface Associates, Laguna Niguel, California, USA). Gas exchange responses were interpolated to 1-s intervals and averaged every 15 s.

Heart rate and cardiac output (\dot{Q}) were determined every 15 s using a non-invasive thoracic bioimpedance device (PhysioFlow PF-05; Manatec Biomedical, Paris, France). The reliability of using this technique to determine \dot{Q} in 10- to 11-year-old children during maximal exercise has a typical error score of 9% over three repeat cycle tests.¹⁸ Arterial-venous O_2 content difference ($C_{(a-v)}O_2$) was estimated via rearrangement of the Fick equation:

$$C_{(a-v)}O_2 = \frac{\dot{V}O_2}{\dot{Q}}$$

A fingertip capillary blood sample was taken within 30 s after the ramp test and analysed for [lactate] (YSI 2300; Yellow Springs, Ohio, USA).

Criteria for establishing maximal oxygen uptake

A plateau in the $\dot{V}O_2$ profile during the ramp test was identified using the methods described by Day *et al.*²³ Briefly, a linear regression was plotted over the 'linear' portion of the $\dot{V}O_2$ response, defined as data points lying after the initial 2 min of exercise and 3 min before exhaustion. The profile of $\dot{V}O_2$ at exhaustion was characterised by extrapolating the linear regression function to exhaustion and examining the last 60 s of the residuals against the extrapolated line (fig 1). A negative residual indicated a deceleration in $\dot{V}O_2$ against power output and was considered a 'plateau' if the magnitude of the residuals was $\geq 5\%$ of the projected $\dot{V}O_2$ (ie, $\dot{V}O_2$ was $\leq 95\%$ of the projected $\dot{V}O_2$). Conversely, a positive residual $\geq 5\%$ of the projected $\dot{V}O_2$ represented an acceleration of $\dot{V}O_2$ close to exhaustion (ie, $\dot{V}O_2$ was $\geq 105\%$ of the projected $\dot{V}O_2$). Positive or negative residuals $< 5\%$ of the peak power output projected $\dot{V}O_2$ was classified as a linear response ($\dot{V}O_2$ was $> 95\%$ but $< 105\%$ the projected $\dot{V}O_2$).

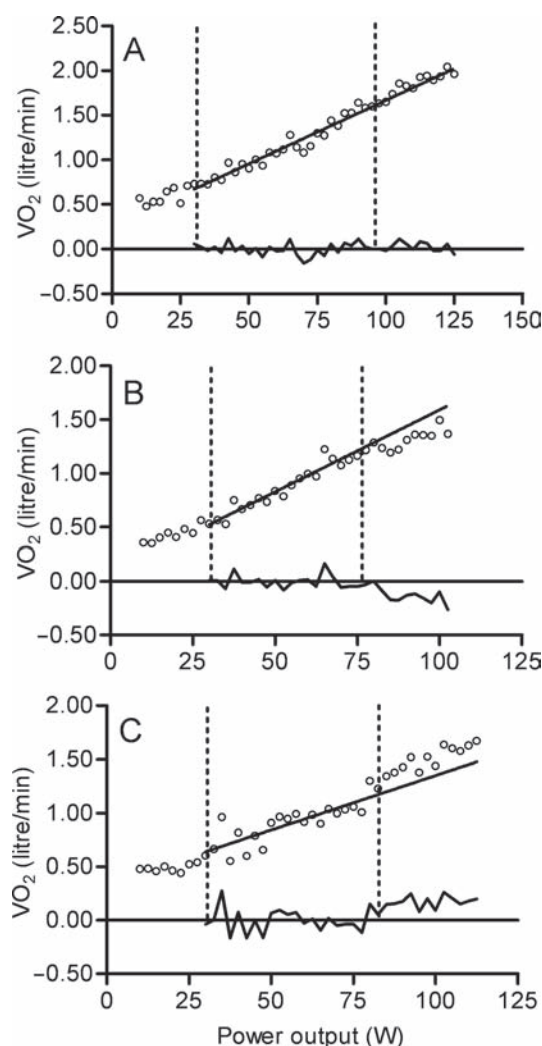


Figure 1 Analysis of the $\dot{V}O_2$ –power output responses during ramp exercise. The solid line represents the linear regression function that was fitted from 2 min (30 W) to 3 min before exhaustion occurred (boundaries demarcated by vertical dotted lines). The extrapolated regression fit is extended following the second vertical line to end exercise, where in A, B and C a linear, plateau and accelerated $\dot{V}O_2$ response is shown, respectively. The residuals from the regression model are plotted on the horizontal line.

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The secondary criteria used to verify a $\dot{V}O_{2\max}$ were taken from key texts and recent publications in paediatric exercise physiology.^{6 19 20 24} These included an RER of 1.00, a heart rate of 195 beats/min and within 85% of age-predicted maximum ($220 - \text{age}$) and a blood [lactate] of ≥ 6 mM.

Statistical analyses

Boys' ($n=8$) and girls' ($n=5$) data were grouped ($n=13$) to form a single data set for analysis. Paired-samples t tests were used to examine mean differences between outcome variables, with the Bonferroni correction applied when multiple comparisons were performed. Limits of agreement analyses were used to establish the mean bias and 95% confidence limits between outcome variables.²⁵ The null hypothesis was rejected at an α level of 0.05. Analyses were performed using SPSS V.15.0 (Chicago, Illinois, USA) and GraphPad Prism (GraphPad Software Inc., San Diego, California, USA).

RESULTS

Ramp validation criteria

Table 1 presents the individual physiological responses during the ramp exercise in accordance with the validation criteria.

Oxygen uptake

The mean duration for the ramp test was 656 s (SD 88), which corresponded to a peak power output of 120 W (SD 15). The ramp test elicited a mean $\dot{V}O_{2\text{peak}}$ of 1.690 litre/min (SD 0.284), which was not significantly different from the $\dot{V}O_{2\text{peak}}$ predicted from peak power output using the linear $\dot{V}O_2$ -power output relationship (1.721 litre/min (SD 0.304), $p=1.0$). The mean goodness of fit (R^2) for the linear function was 0.90 (SD 0.07). Analysis of the individual $\dot{V}O_2$ -power output profiles revealed a range of responses at exhaustion. Four participants (one boy, three girls) were characterised with a mean fall in $\dot{V}O_2$ from the extrapolated linear regression by -0.173 litre/min, consistent with a plateau-like profile. Seven participants (five boys, two girls) were characterised by a linear $\dot{V}O_2$ profile at exhaustion, showing only a small fall in $\dot{V}O_2$ from the predicted value (mean -0.034 litre/min). Finally, two participants (two boys) exhibited an acceleration in $\dot{V}O_2$ near to exhaustion, with a mean increase in $\dot{V}O_2$ of 0.098 litre/min from the linear extrapolation.

Respiratory exchange ratio

At exhaustion the mean RER was 1.11 (SD 0.06, range 0.99–1.20). A single boy failed to reach the RER criterion. In the 12 participants who satisfied this criterion, the $\dot{V}O_2$ recorded at an RER of 1.00 (1.293 litre/min (SD 0.265)) significantly underestimated the $\dot{V}O_2$ recorded at exhaustion (1.681 litre/min (SD 0.295), $p=0.002$), representing 77% of the latter. The limits of agreement showed the RER criterion to underestimate $\dot{V}O_{2\max}$ by a mean bias of -0.388 litre/min (95% confidence limits: -0.911 to 0.136 litre/min, fig 2).

Heart rate

Mean heart rate at exhaustion was 202 beats/min (SD 7, range 191–214). All children satisfied the 85% of their age-predicted maximum criterion (equivalent to ~ 179 beats/min). Three children failed to reach the 195 beats/min criterion despite a clear plateau-like profile in $\dot{V}O_2$ at exhaustion in two of these participants (see table 1). In the participants who satisfied the heart rate criteria, the $\dot{V}O_2$ recorded at 85% of their age-predicted maximum (1.345 litre/min (SD 0.228)) and at 195 beats/min (1.556 litre/min (SD 0.265)) significantly underestimated the $\dot{V}O_2$ recorded at exhaustion (1.690 litre/min (SD 0.284) and 1.721 litre/min (SD 0.318), respectively; $p<0.002$), representing 80% and 90% of the latter. The limits of agreement analyses revealed the 85% age-predicted maximum and 195 beats/min criteria to underestimate $\dot{V}O_{2\max}$ by a mean bias of -0.345 litre/min (95% confidence limits: -0.612 to -0.079) and -0.165 litre/min (95% confidence limits: -0.339 to 0.010 litre/min), respectively (fig 2).

Blood [lactate]

Mean blood [lactate] after ramp exercise was 6.7 mM (SD 2.1, range 4.2–12.1). Six children (four boys, two girls) satisfied the blood [lactate] criterion of ≥ 6 mM. Of the seven participants who had a blood [lactate] <6 mM, two had a plateau in their $\dot{V}O_2$ profile at exhaustion (see table 1).

Ramp and supramaximal responses

The physiological responses during the ramp and supramaximal exercise tests are presented in table 2. The mean time to exhaustion during the supramaximal bout was 91 s (SD 26) at a mean power output of 127 W (SD 16). Using the linear extrapolation from the ramp test, this power output corresponded to a target $\dot{V}O_{2\text{peak}}$ of 1.799 litre/min (SD

Table 1 Participants' ramp test responses in relation to traditionally used validation criteria

Participant	Sex	Ramp $\dot{V}O_{2\text{peak}}$ (litre/min)	$\dot{V}O_2$ plateau	$\dot{V}O_2$ at RER ≥ 1.00 (litre/min)	$\dot{V}O_2$ at 195 beats/min (litre/min)	$\dot{V}O_2$ at 85% age-predicted heart rate (litre/min)	Blood [lactate] ≥ 6 mM
1	M	1.213	No	1.002	1.203	0.921	No
2	M	1.972	Yes	1.733	1.879	1.507	Yes
3	M	1.649	No	1.319	1.469	1.354	No
4	M	1.802	No	Not achieved	1.622	1.357	No
5	M	1.326	No	1.154	1.154	1.006	No
6	M	1.673	No	0.982	Not achieved	1.603	Yes
7	M	1.908	No	1.755	1.618	1.478	Yes
8	M	2.042	No	1.280	1.830	1.586	Yes
9	F	1.598	Yes	1.357	Not achieved	1.411	No
10	F	1.416	Yes	1.047	1.364	1.047	Yes
11	F	1.724	No	1.552	1.532	1.430	No
12	F	2.158	No	1.200	1.891	1.563	Yes
13	F	1.494	Yes	1.137	Not achieved	1.222	No

Where M and F denote male and female respectively. See Results section for further analyses.

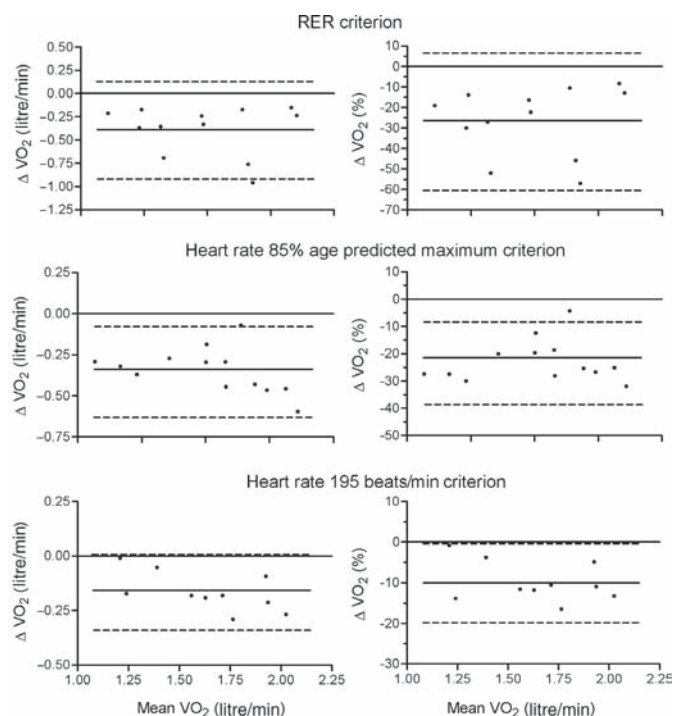


Figure 2 Bland–Altman plots for the secondary criteria. Plots show the mean bias (floating solid line) and 95% confidence limits (floating dotted lines) for the $\dot{V}O_2$ recorded at an RER of 1.00 (top), a heart rate at 85% age-predicted maximum (middle) and at 195 beats/min (bottom) compared with the $\dot{V}O_2$ recorded at exhaustion during the ramp test in absolute terms (left column) and as a percentage difference (right column).

Table 2 Peak physiological responses during the ramp and supra-maximal tests

Variable	Ramp	Supramaximal	p Value
$\dot{V}O_2$ peak (litre/min)	1.690 (0.284)	1.615 (0.307)	0.09
Heart rate peak (beats/min)	202 (7)	196 (8)	<0.001
RER peak	1.11 (0.06)	1.07 (0.13)	0.23
Cardiac output peak (litre/min)	15.10 (4.82)	14.64 (4.51)	0.12
Oxygen extraction peak (ml/min per 100 ml)	12.61 (2.57)	12.28 (2.50)	0.26

Data are reported as mean (SD).

0.342). The $\dot{V}O_{2peak}$ during supramaximal exercise (1.615 litre/min (SD 0.307)) was significantly lower than the target value (1.799 litre/min, $p=0.002$) but was comparable to the $\dot{V}O_{2peak}$ obtained during the ramp test (1.690 litre/min (SD 0.284), $p=0.09$). The limits of agreement for the $\dot{V}O_{2peak}$ achieved during supramaximal and ramp exercise are shown in fig 3. A mean bias of -0.075 litre/min corresponds to $\sim 4\%$ of the initial ramp test $\dot{V}O_{2peak}$ score (95% confidence limits: -0.263 to 0.112 litre/min or -16% to 6%). No significant mean differences were identified for \dot{Q} and $C_{(a-v)}O_2$ between the ramp and supramaximal protocols. Supramaximal exercise was however associated with a lower peak heart rate than ramp exercise.

DISCUSSION

The main findings from the current study are that during ramp cycling exercise in a group of healthy 9- to 10-year-old children, (1) a plateau (or deceleration) in the $\dot{V}O_2$ profile at exhaustion

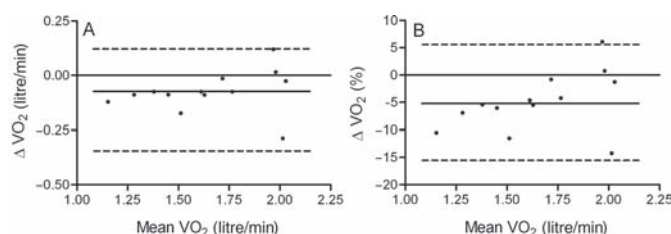


Figure 3 Bland–Altman plots showing the agreement between the $\dot{V}O_2$ recorded at exhaustion during ramp and supramaximal testing. Plots show the mean bias (floating solid line) and 95% confidence limits (floating dotted lines) for the $\dot{V}O_2$ recorded at exhaustion during ramp and supramaximal exercise in absolute terms (A) and as a percentage difference (B).

is an infrequent phenomenon, occurring in $\sim 30\%$ of children; (2) adherence to commonly used secondary criteria to validate a maximal effort in young people can result in either a sub-maximal $\dot{V}O_{2max}$ or a rejection of a participant's $\dot{V}O_{2max}$ score despite a plateau being evident; (3) supramaximal testing at 105% of the power output achieved during ramp exercise did not increase the $\dot{V}O_{2peak}$ achieved compared to the ramp test, thus suggesting the achievement of a true $\dot{V}O_{2max}$ during the initial ramp test; and (4) the changes in the components of the Fick equation, that is maximal \dot{Q} and O_2 extraction ($C_{(a-v)}O_2$), were similar during ramp and supramaximal exercise, further supporting the notion that a true $\dot{V}O_{2max}$ was recorded during the ramp test.

The findings from the present study are consistent with the well-documented finding that a plateau in a child's $\dot{V}O_2$ profile during incremental exercise is not commonplace. However, the absence of plateau is not exclusive to young people. A recent study by Day *et al*²³ determined $\dot{V}O_{2max}$ in 71 adults using a ramp cycling protocol and reported a plateau in $\sim 20\%$ of the participants; a value similar to the current investigation. Interestingly, these authors and others^{22 26} have observed an appreciable rise in $\dot{V}O_2$ at exhaustion in $\sim 30\%$ of their participants, with the remaining $\dot{V}O_2$ responses ($\sim 50\%$) being linear. Such profiles for $\dot{V}O_2$ are consistent with the data presented in the current study, indicating the plateau issue is equally problematic when testing children and adults during a ramp-based cycling exercise protocol.

Given the rare occurrence of a $\dot{V}O_2$ plateau in young people, in addition to the presence of subjective indications of intense effort, secondary criteria have been adopted, either in isolation or in combination, to verify a $\dot{V}O_{2max}$ measure. In the present study, we have taken commonly used secondary criteria from the scientific literature^{6 19 20} and demonstrated that their use can underestimate a child's $\dot{V}O_{2max}$ score by 10–22% on average. Specifically, an RER of 1.00 was the least robust criterion to verify a $\dot{V}O_{2max}$, followed by the heart rate criterion of attaining 85% of an age-predicted maximum. The Bland–Altman plot (fig 2) indicates that an underestimation in an individual's $\dot{V}O_{2max}$ in the order of 60% and 40% is possible for the RER and 85% age-predicted maximum heart rate criterion measures, respectively. Attaining a heart rate of 195 beats/min was found to be the most robust secondary criterion to verify a $\dot{V}O_{2max}$ score, although its application is limited as only three participants achieved a $\dot{V}O_2$ within 5% of their measured $\dot{V}O_{2max}$ (fig 2), which is considered as the typical within-subject diurnal variation of $\dot{V}O_{2max}$ in children¹⁸. Moreover, the Bland–Altman plot indicates that for a given individual, an underestimation of

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~20% is possible using the 195 beats/min criterion. It is also pertinent to note that three participants failed to attain a heart rate of 195 beats/min despite the presence of a plateau in two of these participants. A similar situation was found for two participants using the blood [lactate] criterion of 6 mM. That is, based on the criterion adopted, these participants would be falsely rejected from a study sample because of their failure to achieve an arbitrary criterion imposed by the researcher. Conversely, if a researcher was to use a less robust criterion, that is, a heart rate of 85% predicted maximum, which most of the participants are likely to satisfy, the consequence will be a submaximal and therefore invalid $\dot{V}O_{2\max}$ measurement.

The results from this study suggest that researchers should discontinue the use of secondary criteria to validate a $\dot{V}O_{2\max}$ score in young people. Indeed, given the large variability that is observed for RER (~0.94–1.20), heart rate (~190–215 beats/min) and blood [lactate] (~3–14 mM) at exhaustion in young people,^{13 14 19} this limited application of a 'one size fits all' criterion (or multiple criteria) to verify a $\dot{V}O_{2\max}$ is not surprising. A key question, however, is how can test procedures be standardised to provide a valid and practical measurement of $\dot{V}O_{2\max}$ in young people within a single testing session?

The answer to this question potentially has its origins in the seminal work by Taylor *et al*⁹ who outlined the protocol and criteria needed to determine $\dot{V}O_{2\max}$. Specifically, participants were required to run to exhaustion on a series of 3-min constant-speed treadmill tests at increasing gradients (2.5% increments) on separate days, until a point (gradient) was reached where the rise in $\dot{V}O_2$ was less than that expected (<2.1 ml/kg per minute) when compared to the previous gradient. This 'leveling off' (the plateau) of $\dot{V}O_2$ with increasing exercise intensity was taken as evidence that $\dot{V}O_{2\max}$ had been attained.⁹

In keeping with the use of constant-load exercise, Rossiter *et al*²⁶ had participants perform, after a 5-min rest to recovery from a standard ramp test, a constant-load exercise bout to exhaustion at 105% peak power output (supramaximal exercise). No significant increase in $\dot{V}O_2$ was noted during the supramaximal bout when compared to the ramp test. Therefore, the composite $\dot{V}O_2$ profile from the ramp and supramaximal tests can be used to reveal the plateau criterion within a single testing session, despite the plateau not being evident in the initial ramp test.

The current investigation extended this work to children and found no mean differences in $\dot{V}O_{2\text{peak}}$ between the ramp and supramaximal protocols. This was despite the latter being at a 5% higher power output in an attempt to drive $\dot{V}O_2$ to a greater amplitude. This finding therefore suggests that the final $\dot{V}O_2$ achieved during the ramp test, irrespective of whether a plateau was observed, does represent a true $\dot{V}O_{2\max}$ in children. However, as cautioned by Day *et al*,²³ without performing the additional supramaximal test 'one cannot be certain' that $\dot{V}O_{2\max}$ has been attained. Indeed, the Bland–Altman plot in fig 3 is consistent with this, as one participant was able to elicit a 6% rise in $\dot{V}O_2$ during the supramaximal bout. For this participant, an additional constant-load test, perhaps on a separate day or after ~30 min rest, at 110% peak power would be required to confirm their $\dot{V}O_{2\max}$. However, because most of the participants (92%) in the current study failed to increase their $\dot{V}O_2$ during the supramaximal test, a single constant-load test is likely to be sufficient in most cases.

The present study has shown that a group of healthy children, who were initially habituated to the experimental procedures, are capable of tolerating two exhaustive exercise tests (ramp and supramaximal) within a single session, interspersed with a short recovery phase, for determination of their $\dot{V}O_{2\max}$. This is in agreement with studies conducted with adult participants who were either well accustomed to exercise to exhaustion in the laboratory setting or of an athletic status.^{26 27} In the current study, we elected to use a 15-min recovery period between the ramp and supramaximal test, which is longer than the 1- to 10-min recovery periods used in adult studies.^{26 27} Whether children can tolerate a shorter recovery period is unknown but seems plausible given their faster recovery of metabolic markers ($\dot{V}O_2$, phosphocreatine, blood [lactate], cellular acidosis) after maximal exercise.^{28–30}

In the current study, the intensity of the supramaximal bout was set at 105% ramp test peak power output. The mean test duration was 91 s (SD 26), which is similar to the duration of 88 s (SD 15) reported by Rossiter *et al*²⁶ in adults at the same exercise intensity. Because of the characteristics of the power-duration curve, a higher power output during the supramaximal bout will result in a shorter test duration that may preclude a child from attaining their $\dot{V}O_{2\max}$ because of insufficient time for the $\dot{V}O_2$ response to fully develop. Likewise, although theoretically an individual can attain their $\dot{V}O_{2\max}$ when exercising at a submaximal intensity above critical power (severe exercise domain),³¹ from a conceptual viewpoint this fails to satisfy the $\dot{V}O_{2\max}$ plateau concept—a leveling off of $\dot{V}O_2$ with an increase in exercise intensity. Consequently, the intensity of the constant-load test should be above the ramp test peak power output (ie, supramaximal). Using 105% of the ramp determined peak power output therefore appears an appropriate trade-off between the intensity of the supramaximal bout and being of sufficient duration to allow the $\dot{V}O_2$ to reach its asymptote (ie, $\dot{V}O_{2\max}$).

What is already known on this topic

- ▶ The traditional paradigm for $\dot{V}O_{2\max}$ determination requires the existence of a $\dot{V}O_2$ plateau at exhaustion, yet this is only observed in a minority of children.
- ▶ Researchers have therefore relied on the use of secondary criteria (heart rate, RER and blood [lactate]) to verify subjective criteria of $\dot{V}O_{2\max}$ determination in this population.

What this study adds

- ▶ Widely used secondary criteria underestimate a child's $\dot{V}O_{2\max}$ score by 10–22% on average and can falsely reject a 'true' $\dot{V}O_{2\max}$ score.
- ▶ Researchers should abandon the use of secondary criteria to verify a $\dot{V}O_{2\max}$ in children and adopt the utility of a supramaximal exercise bout, following the initial incremental test, as the method of choice to verify a true $\dot{V}O_{2\max}$.

In conclusion, the use of secondary criteria to verify a maximal effort in young people during ramp cycling exercise can result in the acceptance of a submaximal $\dot{V}O_{2\max}$ and should be abandoned by researchers. In contrast, as supramaximal testing elicits a $\dot{V}O_{2\text{peak}}$ similar to the ramp protocol, thus satisfying the plateau criterion despite only been present in 30% of the initial ramp responses, it is recommended that the use of such tests should be adopted as the appropriate method of confirming a true $\dot{V}O_{2\max}$ in healthy young people. However, further work is needed to establish whether the use of supramaximal testing is appropriate to verify a $\dot{V}O_{2\max}$ in paediatric populations with slow $\dot{V}O_2$ kinetics or a poor ability to tolerate maximal exercise (eg, diseased children).

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